Monitoring and Analysis of Vertical and Horizontal Deformations of a Large Structure Using Conventional Geodetic Techniques

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Abstract
For the reason that there are several factors that affect large engineering structures, monitoring them to determine their deformations for safety purpose cannot be underestimated. Therefore, this study presents monitoring and analysis of vertical and horizontal deformations of a large structure, Palm House Building, Benin City, to determine its structural integrity. Four reference stations, two sets of monitoring points and two conventional geodetic techniques, total station and digital level were used. The positions and heights of the reference stations were respectively determined using CHC900 dual frequency GNSS receivers and digital level with respect to nearby control station and benchmark. The two sets of monitoring points were observed at three epochs at interval of six months using total station and digital level with respect to the reference stations. The observations were adjusted with least squares technique to determine the reliability as well as the accuracy of the adjusted observations and those of the adjusted parameters. The adjusted parameters were used to compute the displacement magnitudes. The computed displacement magnitudes were compared with their respective 95% confidence ellipses/intervals to determine if significant movement has taken place between observation epochs. The study results show that the structure was stable during the period of monitoring.
Keywords: Monitoring, Analysis, Deformation, Large Structure, Palm House Building, Conventional Geodetic Techniques

1. Introduction

Deformation monitoring is an indispensable contribution of geomatics to society and economy. It provides quantitative and reliable information for studying processes in the natural and man-made environment, for risk assessment and for timely adoption of appropriate measures (Wieser and Capra, 2017). The deformation of any large structure is simply the variation of its position, size and shape with respect to its original state or its designed shape. Measuring the deformations of an engineering structure is not just the calculation of the exact positions of the observed object but the variation of these positions with time. The general need for monitoring large structures is well known to the general public as well as engineers due to the loss of human lives in various countries when large structures fail.

Conventionally, deformation monitoring as well as structural integrity of large structures determination is carried out with the terrestrial surveying methods using Theodolites/total-stations, digital levels and similar surveying equipment such as Electronic Distance Measurement, EDM.

The total station measures horizontal and vertical angles and slope distances to each prism from which easting, northing and height values and subsequently displacements are computed. Total station coordination monitors deformation of buildings through the variation of coordinates of observed points. This method offers acceptable accuracy without demanding high visibility or heavy workload. The use of total station surveying instruments for monitoring structures movement gives accurate and good results. The application of total station to monitor building stability is still widely used (Eteje, et al 2018).

Geometric levelling is the oldest method of geodetic surveying, used to measure differences in elevations between two or more points at the Earth's surface. Experience has shown geometric levelling to be a reliable and very precise vertical displacement measurement method. Modern electronic levels, with automatic reading and recording, have significantly improved geometric levelling operational performances (Henriques and Casaca, 2007, Vintilă et al, 2014, and Eteje et al, 2018). For high precision geometric levelling, digital levels should be

used. Those levels are automatic levels with a system of digital image processing that allows automatic reading from a special rod, coded bar, and electronic recording. In this way, all the errors caused by man reading and by manual recording are eliminated and also the speed of levelling increases.

Using the conventional geodetic methods such as total station and digital level, the monitoring scheme is designed such that reference points are established on stable grounds/platforms round the monitored structure, monitoring points are fixed on strategic parts of the structure, at specified interval such as three, six or twelve months, observations are taken. Each of the epochs observations are processed and adjusted separately using least squares technique to determine the most probable values of the coordinates of the monitoring points as well as the accuracy of the adjusted observations and those of the adjusted parameters. The adjusted parameters of the epochs observations are compared to determine displacement of the monitored structure. To determine if the computed displacement is actual movement of the monitored structure or movement has actually taken place between observation epochs, deformation analysis is carried out. Carrying out deformation analysis requires the comparison of the computed displacements and the 95% confidence ellipses/intervals by the application of the accuracy as well as the standard errors of the adjusted parameters. Monitoring the deformation of a large structure enables its structural integrity to be determined.

The monitored structure is Palm House Building in Benin City, Edo State, Nigeria. Palm House is one of the Edo State Secretariat buildings (eleven story building) which consist of three ministries and other offices. The building being a public one attracts a very large population (load). The building has been in existence for more than forty years as it was commissioned in 1973. It is an old building. Findings revealed that no monitoring has been carried out on the building since its construction. Large engineering structures are affected by various factors such as: excessive loads, ground water level variation, plate tectonic movement, changes in the bedrock, changes in the properties of the materials with which they are constructed as a result of change in temperature and age. Since ground water level varies and the foundation of the building is not visible to human eyes, and considering the fact that age and change in temperature affect the properties of the material with which any engineering structure is constructed and the population (load) on the building, the need to investigate or monitor the building (Palm House) for safety purpose is paramount.

The aim of the study is to monitor and analyze the vertical and horizontal deformations of a large structure, Palm House Building in Benin City, using conventional geodetic techniques with a view to detecting any significant movement of the building. Its objectives are to:

1. Carry out observations (Levelling and Total Station observations) at three different epochs at interval of six months and processing of the observations to determine the coordinates and heights of the monitoring networks points.
2. Carry out least squares adjustment and statistical evaluations on the observations to determine the reliability as well as the accuracy of the adjusted observations and those of the adjusted parameters.
3. Compute the displacement magnitudes of the monitoring points and comparing them with their respective 95% confidence ellipses/intervals to determine if significant displacement has taken place between observation epochs.

Palm House (Figure 1) is one of the Edo State Secretariat buildings in Benin City. It is a high rise building located along Benin Sapele Road in Oredo Local Government Area of Edo State. The building is 45m in length, 15m in breadth and 35m in height. It is an eleven story building which consists of various ministries and offices. The study area, Benin City lies between latitudes 06^0 01' 54"N and 06^0 25' 35"N and longitudes 05^0 26' 23"E and 05^0 50' 05"E. Figures 2a to c show the maps of the study area.
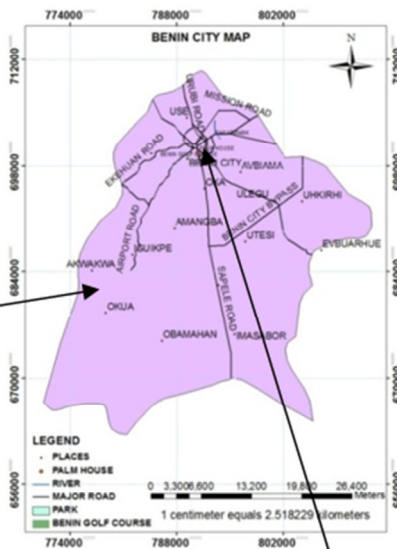
Figure 1: Palm House, Benin City

Figure 2a: Map of Nigeria Showing Edo State.
Source: Ministry of Lands and Surveys, Benin City.

Figure 2b: Map of Edo State Showing Benin City. Figure 2c: Map of Benin City Showing Palm House.
Source: Ministry of Lands and Surveys, Benin City.

Palm House Building

1.1 Least Squares Adjustments by Observation Equation Method

The functional relationship between the adjusted observations and the adjusted parameters is given as (Ono et al, 2014, and Eteje and Oduyebo, 2018):

$$L_a = F(X_a) \tag{1}$$

Where, L_a = adjusted vector of observations and X_a = adjusted station coordinates. Equation (1) is linear function and the general observation equation model was obtained. To make the matrix expression for performing least squares adjustment, analogy will be made with the systematic procedures. The system of observation equations is presented by matrix notation as (Mishima and Endo 2002):

$$V = AX - L \tag{2}$$

Where,

A = Design Matrix
X = Vector of Unknowns
L = Calculated Values (lo) Minus Observed Values (l_b)
V = Residual Matrix

That is,

$$\begin{matrix} V & A & X & L \end{matrix}$$

$$\begin{pmatrix} v_1 \\ v_2 \\ \dots \\ v_m \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \dots & \dots & \dots & \dots \\ a_{m1} & a_{m2} & \dots & a_{mn} \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ \dots \\ x_n \end{pmatrix} - \begin{pmatrix} l_1 \\ l_2 \\ \dots \\ l_m \end{pmatrix} \tag{3}$$

Estimated parameter

$$X = (N)^{-1}(t) \tag{4}$$

Where,

$$N = (A^T W A) = \text{Normal Matrix}$$

$$t = (A^T W L)$$

$$N^{-1} = (A^T W A)^{-1} = Q_{XX}$$

$$X = (A^T W A)^{-1}(A^T W L) = \text{Estimate}$$

W = Weighted Matrix

The models for the computation of the a posteriori variance, $\hat{\sigma}_o^2$ and a posteriori standard error, $\hat{\sigma}_o$ as given by Ameh (2013), and Eteje and Oduyebo (2018) are:

$$\hat{\sigma}_o^2 = \frac{V^T W V}{r} \tag{5}$$

$$\hat{\sigma}_o = \sqrt{\frac{V^T W V}{r}} \tag{6}$$

Where,

r = Degree of freedom

The model for the computation of the standard error of the adjusted parameters is given as (Ameh, 2013):

$$\hat{\sigma}_{xi} = \hat{\sigma}_o \sqrt{Q_{nn}} = \sqrt{\hat{\sigma}_o^2 Q_{nn}} \tag{7}$$

Where,

Q_{nn} is a diagonal element of the inverse of the normal matrix (N^{-1}).

1.2 Distance Observation Equation

The linearized form of distance observation equation as given by Githumbi (2014) is:

$$\frac{dS_{ij}}{dX_i} = -\left(\frac{X_j^o - X_i^o}{S_{ij}^o} \right) \quad \frac{dS_{ij}}{dX_j} = \left(\frac{X_j^o - X_i^o}{S_{ij}^o} \right)$$

$$\left. \begin{matrix} \\ \\ \end{matrix} \right\} \tag{8}$$

$$\frac{dS_{ij}}{dY_i} = -\left(\frac{Y_j^o - Y_i^o}{S_{ij}^o} \right) \quad \frac{dS_{ij}}{dY_j} = \left(\frac{Y_j^o - Y_i^o}{S_{ij}^o} \right)$$

Where, S_{ij}^0 is the distance computed from approximate coordinates, $X_i^o, Y_i^o, X_j^o, X_j^o$ and S_{ij} is the distance computed from the unknown parameters, X_i, Y_i, X_j, Y_j.

1.3 Azimuth Observation Equation

The linearized form of azimuth observation equation is given by Githumbi (2014) as:

$$\left.\begin{array}{cc} \dfrac{dA_{ij}}{dX_i} = \left(\dfrac{Y_j^o - Y_i^o}{S_{ij}^{O2}} \right) & \dfrac{dA_{ij}}{dY_i} = -\left(\dfrac{X_j^o - X_i^o}{S_{ij}^{O2}} \right) \\[4mm] \dfrac{dA_{ij}}{dX_j} = -\left(\dfrac{Y_j^o - Y_i^o}{S_{ij}^{O2}} \right) & \dfrac{dA_{ij}}{dY_J} = \left(\dfrac{X_j^o - X_i^o}{S_{ij}^{O2}} \right) \end{array}\right\}$$

(9)

Where A_{ij} is the computed azimuth.

1.4 Computation of Displacement Magnitude

Once the adjustment of observations is completed, object point displacement, d is computed as the difference in coordinates/heights between the measurement epochs as given by Kaloop and Li, (2009):

$$d = \begin{bmatrix} d_x \\ d_y \end{bmatrix} = \begin{bmatrix} x_c^i - x_c^p \\ y_c^i - y_c^p \end{bmatrix}$$

(10)

Where,

x_c^i, y_c^i = coordinates of last epoch.

x_c^p, y_c^p = coordinates of preceding epoch.

The displacement magnitude is computed as (Kaloop and Li, 2009):

$$|D| = \sqrt{d^T d}$$

(11)

Vertical movement (dH) is computed for each object (monitoring) point as:

$$dH = \sqrt{\left(z_c^i - z_c^p\right)^2} = \sqrt{(dz)^2}$$

(12)

Where,

z_c^i = height of last epoch.

z_c^p = height of preceding epoch.

1.5 Computation of 95% Confidence Ellipses/Intervals

The 95% confidence ellipses/intervals are computed with the standard errors of the adjusted parameters and the 95% confidence level expansion factor, 1.96. In this, the error associated with the observed monitoring point in two different epochs is computed and multiplied by 1.96. The model for the computation of the 95% confidence ellipse is given by Beshr and Kaloop (2013) as:

$$e_n = 1.96.\sqrt{\sigma_f^2 + \sigma_i^2}$$

(13)

Where, σ_f^2 is the standard error squared in position for the (final) or most recent survey, σ_i^2 is the standard error squared in position for the (initial) or reference survey.

1.6 Deformation Analysis

Deformation modelling or analysis is done to determine whether points displacements are significant. To determine the significant of points displacements, the computed displacements are compared with their corresponding 95% confidence ellipses/intervals (Bird, 2009). In the analysis, the computed displacement magnitude is compared with the 95% confidence ellipse/interval to determine if significant movement has taken place between observation epochs. If the computed displacement magnitude, $|D|$ is less than the 95% confidence ellipse/interval, e_n ($|D| < e_n$), it implies that movement did not take place between observation epochs. But if on the other hand, the computed displacement magnitude, $|D|$ is greater than the 95% confidence ellipse/interval, e_n ($|D| > e_n$), it implies that movement has taken place between observation epochs as

explained by Beshr and Kaloop (2013).

2. Methodology

The adopted methodology involved the following stages namely: data acquisition, data processing, result presentation and analysis. Figure 3 shows the flow chart of the adopted methodology.
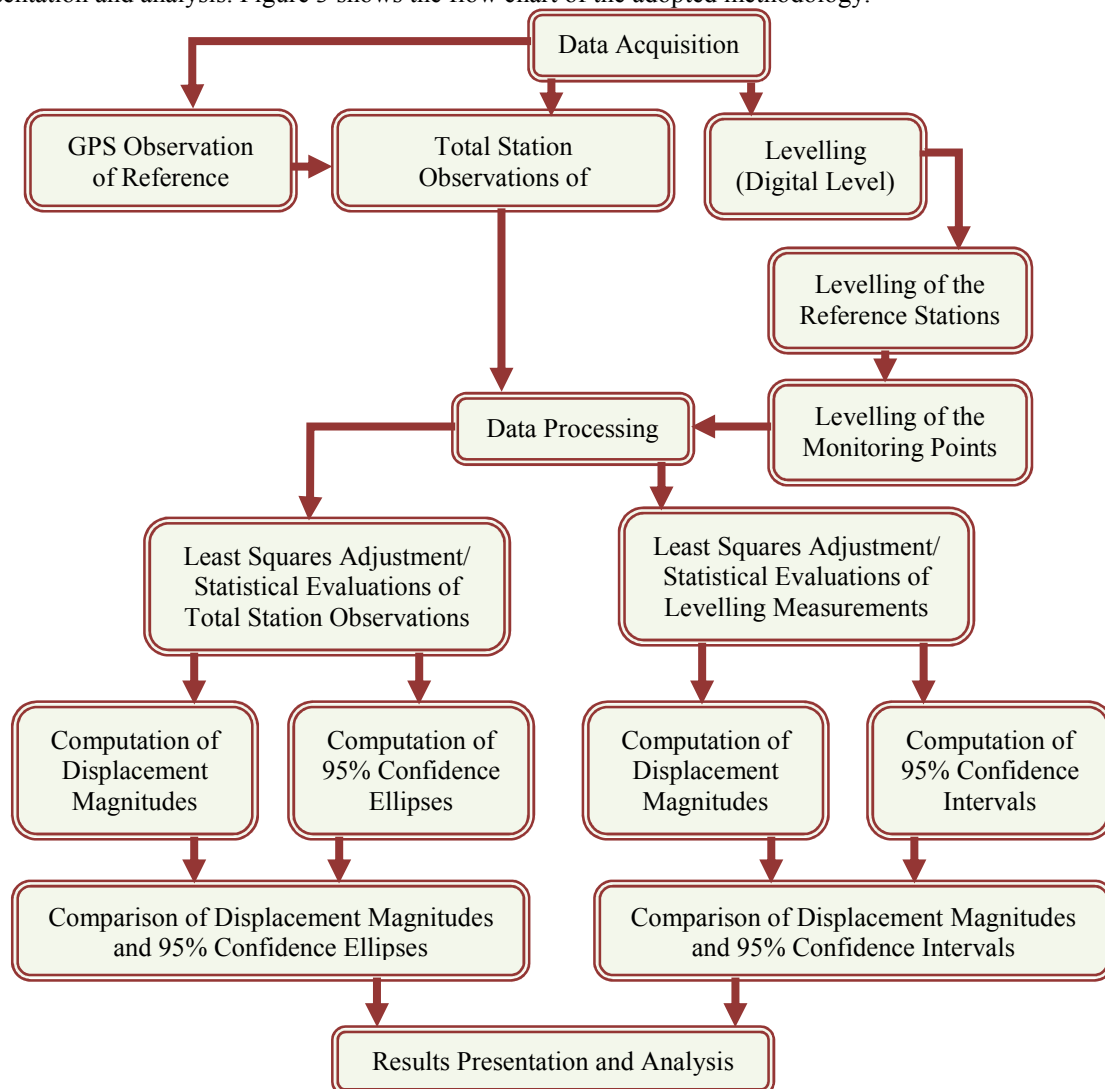

Figure 3: Flow Chart of the Adopted Methodology

2.1 Data Acquisition

Two sets of monitoring points and four reference stations established round the building were used. The positions of the reference stations, A, B, C and D were determined with respect to a control station (FGPEDY06) using CHC900 dual frequency GNSS receivers. The orthometric heights of the reference stations were determined with Sokkia Digital Level (Sokkia SDL50) with respect to a nearby benchmark, BC/BM03. The vertical dimension monitoring points, E, F, G, H, I and J were marked on the building walls about 30cm above ground level so that the levelling staff could be held on them. The horizontal dimension monitoring points, K, L, M and N were marked on the building's roof with concrete nails.

The height differences and heights of the vertical dimension monitoring points were obtained with respect to those of the reference stations using the digital level (see Figure 4) while the coordinates (northings and eastings), bearings and distances of the horizontal dimension monitoring points were obtained with total station also with respect to the reference stations (see Figure 5). The observations of the monitoring points using the two techniques were carried out at three different epochs at interval of six months. The observations were carried out in March, 2016, September, 2016 and March, 2017.
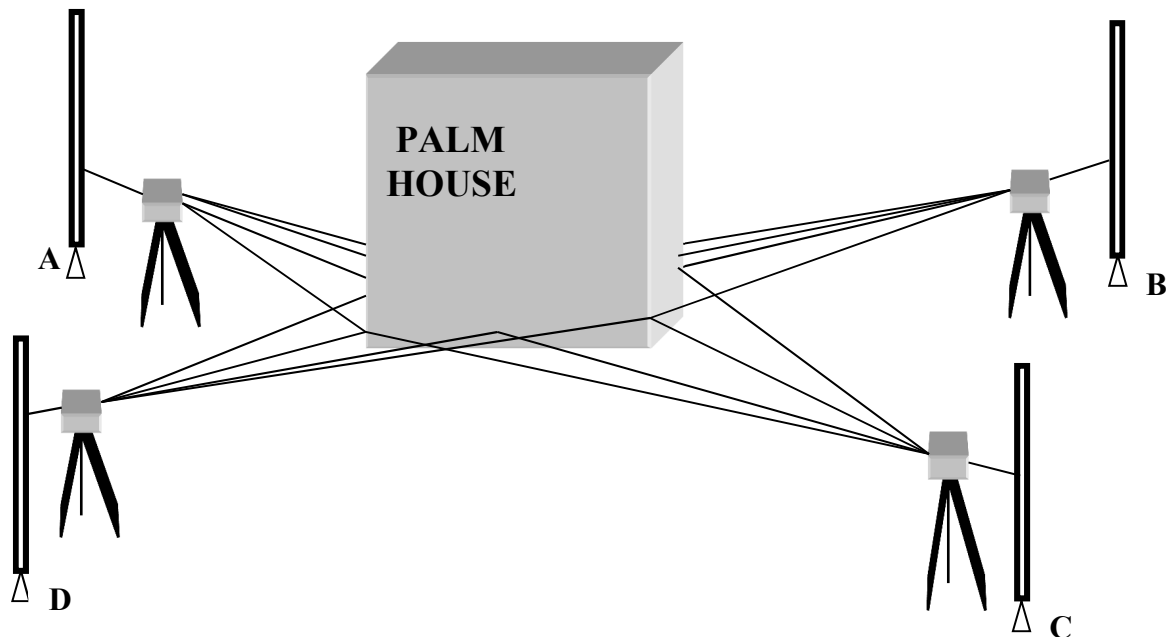
Fig. 4: Levelling of the Monitoring Points with Respect to the Reference Stations
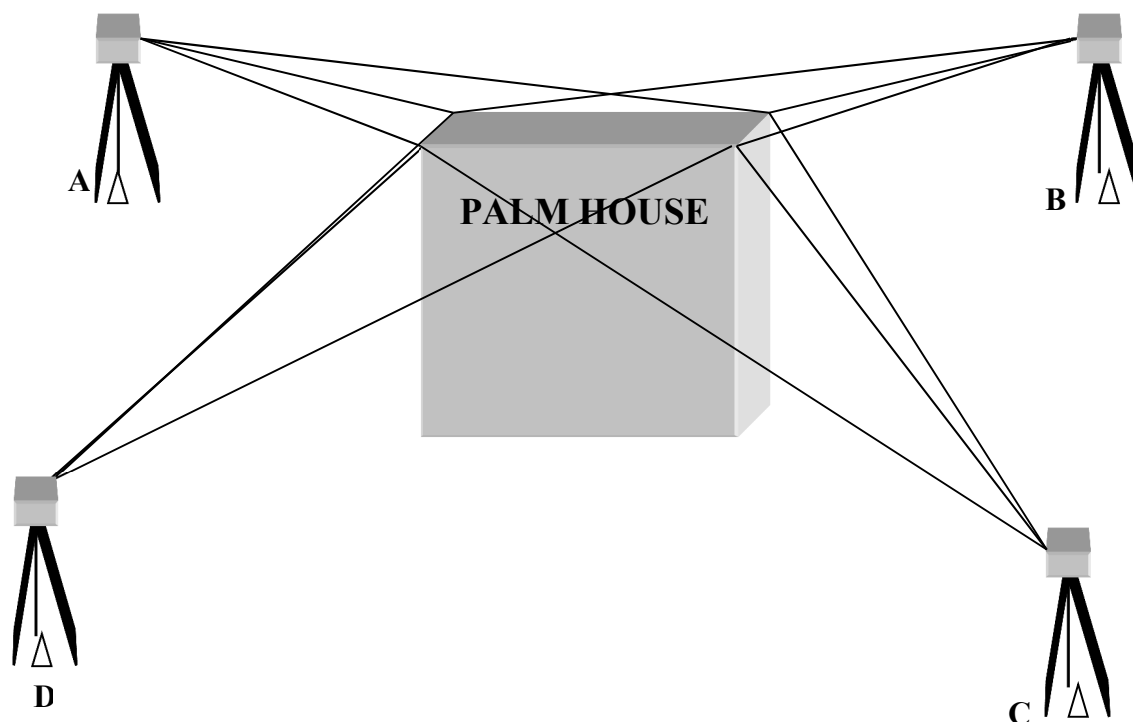

Fig. 5: Horizontal Dimension Monitoring Points Total Station Observation Network

2.2 Data Processing

The digital level and total station observations were adjusted with least squares technique to determine the accuracy as well as the reliability of the adjusted observations and those of the adjusted parameters. The least squares adjustments of the observations were carried using equation (4). The distance and azimuth observation equations of the total station observations were respectively derived/formed using equations (8) and (9). The a posteriori standard errors as well as the accuracy of the adjusted observations (3 epochs) were computed using equation (6). The standard errors of the adjusted parameters were computed using equation (7). The least squares adjustment and statistical evaluations of the observations were carried out with Columbus software.

The displacements of the points were computed by comparing consecutively the adjusted epochs coordinates and heights. The displacements between the first and third epochs observations were also computed.

The displacements of the points as well as the building were computed using equation (10). The displacement magnitudes in horizontal and vertical dimensions were respectively computed using equations (11) and (12). The 95% confidence ellipses/intervals were computed using equation (13).

2.3   Result Presentation and Analysis
2.3.1 Analysis of the Adjusted Observations Using Least Squares Technique
The a posteriori standard errors of the three epochs total station observations were respectively 0.48126m, 0.41917m and 0.42506m which show the high accuracy of the adjusted observations. Also, the a posteriori standard errors of the three epochs digital level measurements were respectively 0.00193m, 0.00195m and 0.00188m which also show the high accuracy of the adjusted levelling.

2.3.2 Comparison between the Computed Displacement Magnitudes and their Respective 95% Confidence Ellipses/Intervals
Table 1 and Figure 6 present the horizontal displacement magnitudes of the monitoring points and their respective confidence ellipses at 95% confidence level. The horizontal displacement magnitudes of the monitoring points/building at six and twelve months intervals were computed and compared with their respective confidence ellipses to determine if significant movement has taken between observation epochs. It can be seen from table 1 and figure 6 that the computed displacement magnitudes of the points were all less than their respective confidence ellipses implying that the building did not undergo any horizontal displacement during the period of survey.

Table 1: Comparison of the Horizontal Displacement Magnitudes with their Corresponding Confidence Ellipses

| MONITORING POINT		K (STABLE)	L (STABLE)	M (STABLE)	N (STABLE)
B/W 1ST & 2nd EPOCHS	$\sqrt{(\Delta N)^2 + (\Delta E)^2}$ (m)	0.0012731	0.0006694	0.0011507	0.0007355
	$1.96.\sqrt{\sigma_f^2 + \sigma_i^2}$	0.0026608	0.0022470	0.0029255	0.0021046
B/W 2nd & 3rd EPOCHS	$\sqrt{(\Delta N)^2 + (\Delta E)^2}$ (m)	0.0008805	0.0008053	0.0010300	0.0006152
	$1.96.\sqrt{\sigma_f^2 + \sigma_i^2}$	0.0012535	0.0014447	0.0014538	0.0013117
B/W 1ST & 3rd EPOCHS	$\sqrt{(\Delta N)^2 + (\Delta E)^2}$ (m)	0.0008509	0.0002280	0.0006537	0.0001304
	$1.96.\sqrt{\sigma_f^2 + \sigma_i^2}$	0.0026608	0.0025025	0.0029352	0.0021100
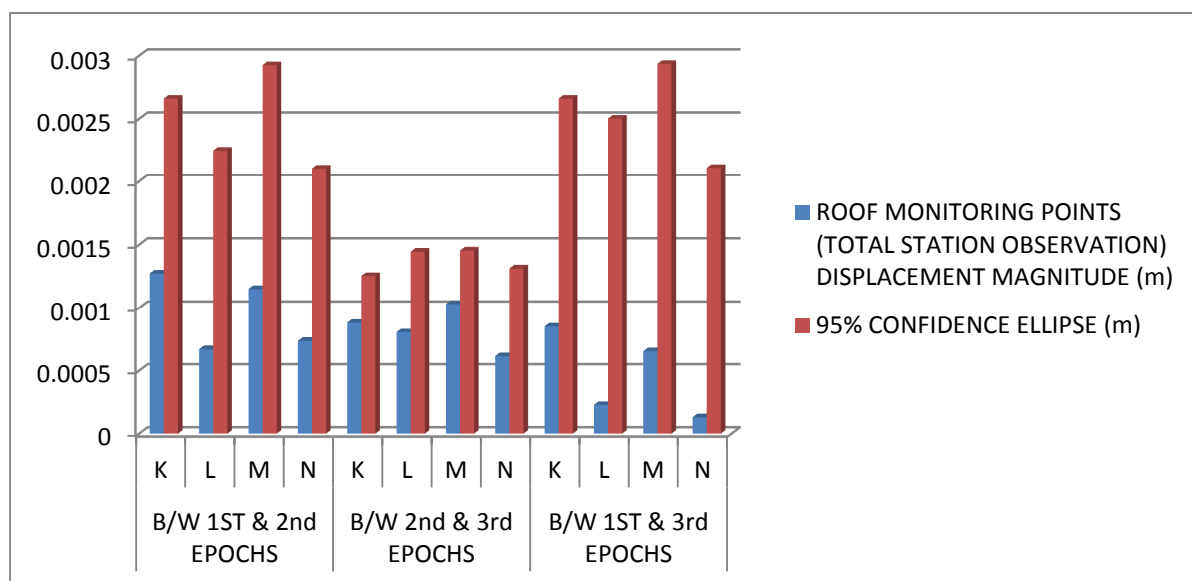
Figure 6: Plot of the Horizontal Displacement Magnitudes and their Corresponding Confidence Ellipses.

Table 2 and Figure 7 also present the vertical displacement magnitudes of the monitoring points and their respective confidence intervals at 95% confidence level. The vertical displacement magnitudes of the building at six and twelve months intervals were computed and compared with their respective confidence intervals to

determine if the reported movements were actual movements of the building. It can as well be seen from table 2 and figure 7 that the computed vertical displacement magnitudes of the structure were all less than their respective confidence intervals implying that the building did not undergo any vertical displacement during the period of survey.

Table 2: Comparison of the Vertical Displacement Magnitudes with their Corresponding Confidence Intervals

| MONITORING POINT		E	F	G	H	I	J
B/W 1ST & 2nd EPOCHS	$\sqrt{(\Delta H)^2}$ (m)	0.0006723	0.0008573	0.0008740	0.0010974	0.0009902	0.0013523
	$1.96\sqrt{\sigma_f^2 + \sigma_i^2}$	0.0252265	0.0320851	0.0257389	0.0230336	0.0308978	0.0239853
B/W 2nd & 3rd EPOCHS	$\sqrt{(\Delta H)^2}$ (m)	0.0006678	0.0009715	0.0006975	0.0009553	0.0009983	0.0012183
	$1.96\sqrt{\sigma_f^2 + \sigma_i^2}$	0.0249371	0.0317334	0.0254468	0.0226900	0.0304597	0.0236637
B/W 1ST & 3rd EPOCHS	$\sqrt{(\Delta H)^2}$ (m)	0.0000045	0.0001142	0.0001765	0.0001421	0.0000081	0.0001340
	$1.96\sqrt{\sigma_f^2 + \sigma_i^2}$	0.0242408	0.0301373	0.0246045	0.0252142	0.0329854	0.0249046
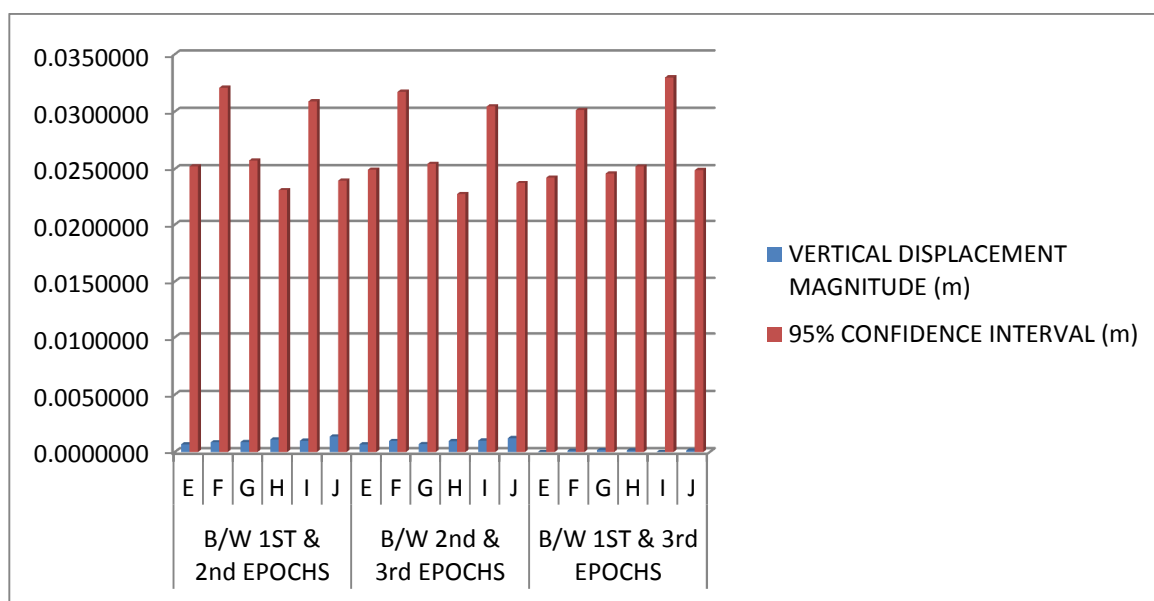
Figure 7: Plot of the Vertical Displacement Magnitudes and their Corresponding Confidence Intervals.

3. Conclusion

Large engineering structures are affected by various factors such as excessive loads, ground water level variation, plate tectonic movement, changes in the bedrock, changes in the properties of materials with which they a constructed as a result of change in temperature and age. As the effect of each of these factors can result in gradual movement of the structures which is not visible to human eyes and thereby lead to the collapse of these large structures, deformation monitoring has become an indispensable contribution of geodesists and engineers to the society and economy. This study has monitored and analyzed the vertical and horizontal deformations of Palm House Building, Benin City, being an old building which has not been monitored since its construction to determine its structural integrity. Four reference stations, two sets of monitoring points and two conventional geodetic techniques were used. The results of the study show that the building was stable during the period of survey. That is, the building is still fit for usage.

4. Recommendation

Based on the findings of this study, the following recommendations were made:
1. That the regularity of the survey as well as observation interval should be increased to twelve months as the survey is ongoing.
2. That the observations should be processed with other adjustment techniques to see if significant movement of the building will be reported.

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